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MERCURY IN WATER AND SEDIMENT OF STEAMBOAT CREEK, NEVADA: IMPLICATIONS FOR STREAM RESTORATION[1]

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ABSTRACT: The objective of this study was to characterize the sources, concentrations, and distribution of total and methylmercury in water, and channel and bank sediments of Steamboat Creek, Nevada. This information was needed to begin to assess the potential impacts of stream restoration on mercury pollution in this tributary to the Truckee River. The Truckee River flows into Pyramid Lake, a terminal water body home to one endangered and one threatened fish species, where stable pollutants will accumulate over time. Mercury in Steamboat Creek was originally derived from its headwaters, Washoe Lake, where several gold and silver mills that utilized mercury were located. In the 100 plus years since ore processing occurred, mercury-laden alluvium has been deposited in the stream channel and on streambanks where it is available for remobilization. Total mercury concentrations measured in unfiltered water from the creek ranged from 82 to 419 ng/L, with greater than 90 percent of this mercury being particle-bound (> 0.45 (m). Mercury in sediments ranged from 0.26 to 10.2 µg/g. Methylmercury concentrations in sediments of Steamboat Creek were highest in wetlands, lower in the stream channel, and still lower in streambank settings. Methylmercury concentrations in water were 0.63 to 1.4 ng/L. A streambank restoration plan, which includes alterations to channel geometry and wetland creation or expansion, has been initiated for the creek. Data developed indicate that streambank stabilization could reduce the mercury loading to the Creek and that wetland construction could exacerbate methylmercury production.
(KEY TERMS: mercury; Steamboat Creek; wetland; methylmercury; stream, restoration.)

INTRODUCTION

Mercury (Hg) is found in the environment as inorganic [i.e., elemental mercury (Hg^0), mercuric species (Hg^{2+})] and organic species [i.e., methylmercury (MeHg), dimethylmercury (Me_2Hg)]. Methylmercury is known to bioaccumulate in aquatic organisms resulting in human health and ecological concerns (Waltras *et al.*, 1994; Hudson *et al.*, 1994). Methylmercury is the dominant form of mercury in fish and aquatic insects. The National Academy of Sciences has recently determined that methylmercury can cause neurological effects on nonhuman primates as a result of low chronic levels of exposure *in utero*. Studies indicated that the nervous system is sensitive to low dose exposures and that human and animal exposures at low levels can affect developing and adult cardiovascular systems (National Academy of Sciences, 2000). Wetlands and anaerobic sediments are thought to be important sites of methylmercury production (St. Louis *et al.*, 1994; Bishop *et al.*, 1995; Krabbenhoff *et al.*, 1995; Morel *et al.*, 1998). Sulfate-reducing bacteria (SRB) are believed to be the major group of microorganisms responsible for methylation of inorganic species of mercury (Compeau and Bartha, 1985; Gilmour *et al.*, 1998). Although currently there is no data available on the mercury concentration in aquatic organisms in Steamboat Creek, mercury concentrations in carp in Washoe Lake, the headwaters of Steamboat Creek exceeded the 1 µg/g human health ingestion/exposure concentration (Hoffman *et al.*, 1987).

A number of hydrologic processes can contribute to the movement and distribution of mercury in aquatic systems. Heavy metals possess a high affinity for particulate matter in surface waters. Up to 90 percent of the total heavy metal load within rivers can be transported in the particulate phase (Salimonas and Forstner, 1984; Gibbs, 1997; Martin and Matbeck,

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1997). This phenomenon would allow for mercury to be deposited and stored along river channels and floodplains during normal sediment transport and larger flood events (Miller, 1997). Miller *et al.* (1999) demonstrated that in contaminated systems, mercury may be stored in large quantities in river and floodplain deposits. Mercury concentrations generally increase as average particle size decreases in fluvial systems (Miller *et al.,* 1999). The processes of erosion, transport, and deposition may control the distribution and availability of mercury in aquatic ecosystems and must be considered when designing stream restoration sites or wetland mitigation projects in mercury contaminated systems. Fluvial depositional areas can be sources, sinks, and sites of methylation for contaminated sediments.

This study investigates mercury contamination in Steamboat Creek, a small urban watercourse that drains Washoe Lake south of Reno, Nevada, and terminates in the Truckee River east of the city (Figure 1). This stream not only has been documented as having high mercury concentrations in water (Lyons *et al.,* 1998), but it is also one of the major contributors of nonpoint source pollution (especially phosphorus, nitrogen, and total suspended sediment) to the Truckee River. The input of pollution to the Truckee River is of special concern because its terminus is landlocked Pyramid Lake, home to the endangered Cui-ui and threatened Lahonton Cutthroat Trout fish species (U.S. Fish and Wildlife, 1999). The input of mercury from Steamboat Creek to the Truckee River raises concerns regarding the health of these endangered fish species and the Pyramid Lake Fisheries. Fish containing µg/g levels of mercury in tissue are found in waters containing only a few ng/L of mercury (Gilmour and Henry, 1991).

To address the nonpoint source pollution issues associated with Steamboat Creek, a steering committee led by Washoe-Storey Conservation District developed a Steamboat Creek Restoration Plan, which calls for alterations to the geometry of the channel and surrounding floodplain, and for wetland mitigation and creation. Since wetlands are sites of known methylmercury production, this study was undertaken to characterize the mercury distribution in the creek, to determine if methylmercury was being produced in different types of aquatic environments, and to develop data that could aid in the development and implementation of a restoration plan that will not lead to the exacerbation of mercury contamination and bioavailability in Steamboat Creek.

Lyons *et al.* (1998) demonstrated that total mercury concentrations in waters of Steamboat Creek were 15 to 53 times higher than natural background (1-3 ng/L). They concluded that the main source of mercury contamination was tailings associated with four mills that processed gold and silver ore in the late 1860s to 1890s, located adjacent to Washoe Lake. The Ophir Mill processed up to 4.5×10^4 kg of ore per day in 1862 (Ansari, 1989). This mill was estimated to be in operation for approximately six years. Given that about 0.45 kg of mercury was estimated to have been lost to the environment for every 1000 kg of ore milled (Smith, 1943), the total amount of mercury in tailings available for distribution along Steamboat Creek could be as much as 40 metric tons. This is a conservative estimate, since eight other mills were also located in the Washoe Valley/Washoe City region that used the same ore processing method. Another potential source of mercury to Steamboat Creek is Steamboat Ditch which traverses the naturally mercury enriched Steamboat Springs geothermal area (Gustin *et al.,* 1999).

STUDY AREA

Steamboat Creek traverses northeast 17.5-miles from Washoe Lake to the Truckee River. It is the principal drainage for Washoe Valley, Pleasant Valley, and Truckee Meadows, Nevada. These three areas encompass approximately 150 km^2. Washoe Lake is a shallow graben lake whose water levels fluctuate significantly with changes in annual precipitation (Figure 1).

In addition to Washoe Lake, the creek drains a number of tributaries originating in the Carson Range along the eastern side of the Sierra Nevada. The primary source of water to these tributaries is spring snowmelt. This side of the basin contains high-relief sub-basins draining igneous intrusive and igneous extrusive terrain. The east boundary of the watershed is the west face of the Virginia Range. This area is comprised of lower relief sub-basins draining areas of complex volcanic terrain. Precipitation events are the primary sources of water on this side (Myers, 1994).

Steamboat Creek has undergone many anthropogenic changes during the past 150 years. Due to the scarcity of water in this high desert region, there have been considerable agricultural diversions, base level drops, and morphologic alterations to Steamboat Creek. These influences have created a channelized, incised, and straightened creek. Many water quality concerns have arisen due to stream degradation in recent years. In its current condition, the Creek is highly prone to bank erosion and elevated sediment loads.

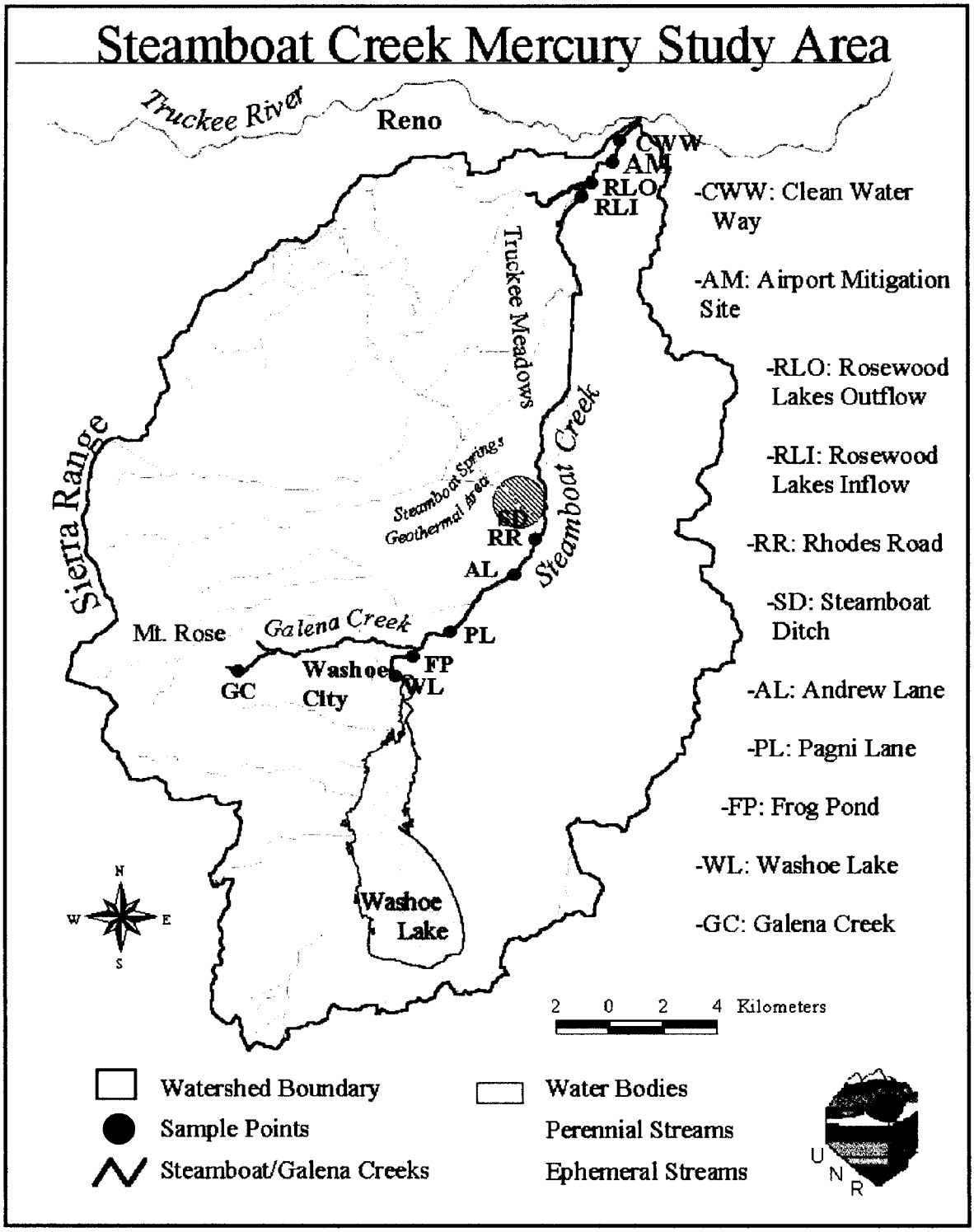

Figure 1. Map of Steamboat Creek, Nevada, Drainage Basin and Sample Locations for This Study.

METHODS

Water samples were collected from Steamboat Creek at Washoe Lake Outflow, Frog Pond, Pagni Lane, Andrew Lane, Rhodes Rhode, Rosewood Lakes Inflow and Outflow, the Airport Mitigation Site, and Clean Water Way (Figure 1). The Frog Pond and Rosewood Lake Inflow sampling sites are areas where

the water significantly decreases in velocity as it enters these broad catchments. The Rhodes Road sampling site is above the confluence of Steamboat Ditch with Steamboat Creek. In addition, waters from a tributary, Galena Creek, and an agricultural diversion canal, Steamboat Ditch, which traverses the Steamboat Springs geothermal area, were sampled (Figure 1). Galena Creek was sampled approximately 8 km upstream from its confluence with the Steamboat Creek, and Steamboat Ditch was sampled immediately before its confluence with Steamboat Creek. Water samples were collected May 26, 1999, and September 1, 1999. Three additional samples were collected on June 15, 1999, at Washoe Lake Outfall, Rhodes Road, and Clean Water Way to assess total mercury (Hg_T) in filtered and nonfiltered samples. Filtered samples were collected using a peristaltic pump (Master Flex) and Teflon® tubing. Samples were filtered through an acid cleaned 0.45-μm Versapor disposable filter (Geotec Inc.). All water samples were taken using the "clean-hands, dirty-hands" protocol (Gill and Fitzgerald, 1987; Gill and Bruland, 1990) and by immersing bottles directly into the water column several inches below the surface microlayer. Teflon® bottles used for sample collection and storage underwent a seven-day cleaning cycle which included a 48-hour, 50 percent nitric acid hot bath and two 24-hour cycles of refluxing with optima hydrochloric acid (Keeler *et al.,* 1995). Immediately following collection, samples were acidified using 1 percent volume-to-volume optima hydrochloric acid and refrigerated.

Total mercury analysis of unfiltered and filtered water samples utilized bromine-monochloride oxidation followed by stannous chloride reduction of Hg^{2+} to Hg^0 (Bloom and Crecelius, 1983). Mercury was carried from solution using ultra-high purity nitrogen gas, and collected on gold-coated quartz sand traps. Traps were analyzed using dual amalgamation and cold vapor atomic fluorescence spectrometry (CVAFS) (Dumarey *et al.,* 1985; Bloom and Fitzgerald, 1988). Triplicate analysis of each sample yielded an average coefficient of variation of 12 percent. Laboratory and field blank total mercury in water concentrations were 1.5 ± 1.5 ng/L.

One set of duplicate water samples collected from Washoe Lake Outflow and Clean Water Way (Figure 1) were analyzed by Frontier Geosciences Inc., Seattle, Washington, for quality control purposes. Total mercury in unfiltered water was determined by Frontier using BrCl oxidation, $SnCl_2$ reduction, dual gold amalgamation, and CVAFS detection (EPA method 1631 modified). The discrepancy between duplicate samples ranged from 6 to 19 percent with the higher percentage associated with higher concentration samples. Additional BrCl reduced this discrepancy. Selected water samples were analyzed for methylmercury by Frontier Geosciences using distillation, aqueous phase ethylation, isothermal GC separation, and CVAFS detection (EPA draft Method 1630 modified; Bloom, 1989).

Sediment samples for mercury analyses were taken at all water sample locations except for Steamboat Ditch (Figure 1). Each sample consisted of a subsample from a homogenized composite of five approximately 500g samples taken within a 50-m radius at each site. Streambank samples were taken on the inset floodplain and stream channel samples were taken in the active channel. Sediments were stored in either 250-ml glass bottles or triple bagged plastic bags and refrigerated prior to analysis. Streambank and stream channel samples were collected on May 26, 1999, and September 1, 1999. Those samples denoted as wetland samples were taken in sediments supporting thriving vegetation on September 1, 1999. The Nevada Bureau of Mines and Geology determined total mercury in sediment by digestion in aqua regia, using a Buck Scientific hydride cold vapor generation system attached to a Perkin Elmer 2380 atomic adsorption spectrometer (Lechler *et al.,* 1995). Frontier Geosciences analyzed methylmercury in sediments by acidic bromide/methylene chloride extraction, aqueous phase ethylation, isothermal GC separation, and CVAFS detection (EPA draft method 1630 modified; Bloom, 1989). Samples for methylmercury analysis were collected in glass bottles provided by Frontier Geosciences, refrigerated and shipped overnight express.

RESULTS

Total mercury (Hg_T) concentrations of unfiltered waters in Steamboat Creek ranged from 182 ng/L to 303 ng/L in May and from 83 ng/L to 419 ng/L in September (Table 1; Figure 2). Highest concentrations were measured in samples collected at Washoe Lake Outfall on both dates. Filtered total mercury concentrations from Washoe Lake Outfall, Rhodes Road, and Clean Water Way ranged from 11 ng/L to 14 ng Hg/L, (Table 1). Concentrations of total mercury in unfiltered samples of Galena Creek were 3.5 ng/L and 6.5 ng/L for the May and September sampling dates, respectively. Total mercury concentrations in unfiltered waters of Steamboat Creek are up to 70 times greater than those found in the pristine Galena Creek waters. The agricultural diversion, Steamboat Ditch, which traverses the mercury enriched geothermal area, had unfiltered total mercury concentrations of 30 ng/L and 17 ng/L for May and September, respectively (Table 1).

TABLE 1. Total Mercury in Unfiltered and Filtered (in parenthesis) Water (ng/L) of Steamboat Creek and Tributaries Collected in May, June, and September, 1999.

Sample Location	May 26, 1999 (ng/L)	June 15, 1999 (ng/L)	September 1, 1999 (ng/L)
Galena Creek	3.5	–	6.5
Steamboat Ditch	30	–	17
Washoe Lake Outflow	303	265 (11)	419
Andrew Lane	246	–	302
Rhodes Road 1	274	173 (12)	131
Rhodes Road 2	262	–	–
Rosewood Lakes Outflow	258	–	215
Clean Water Way 1	185	244 (12)	114 (14)
Clean Water Way 2	182	–	83

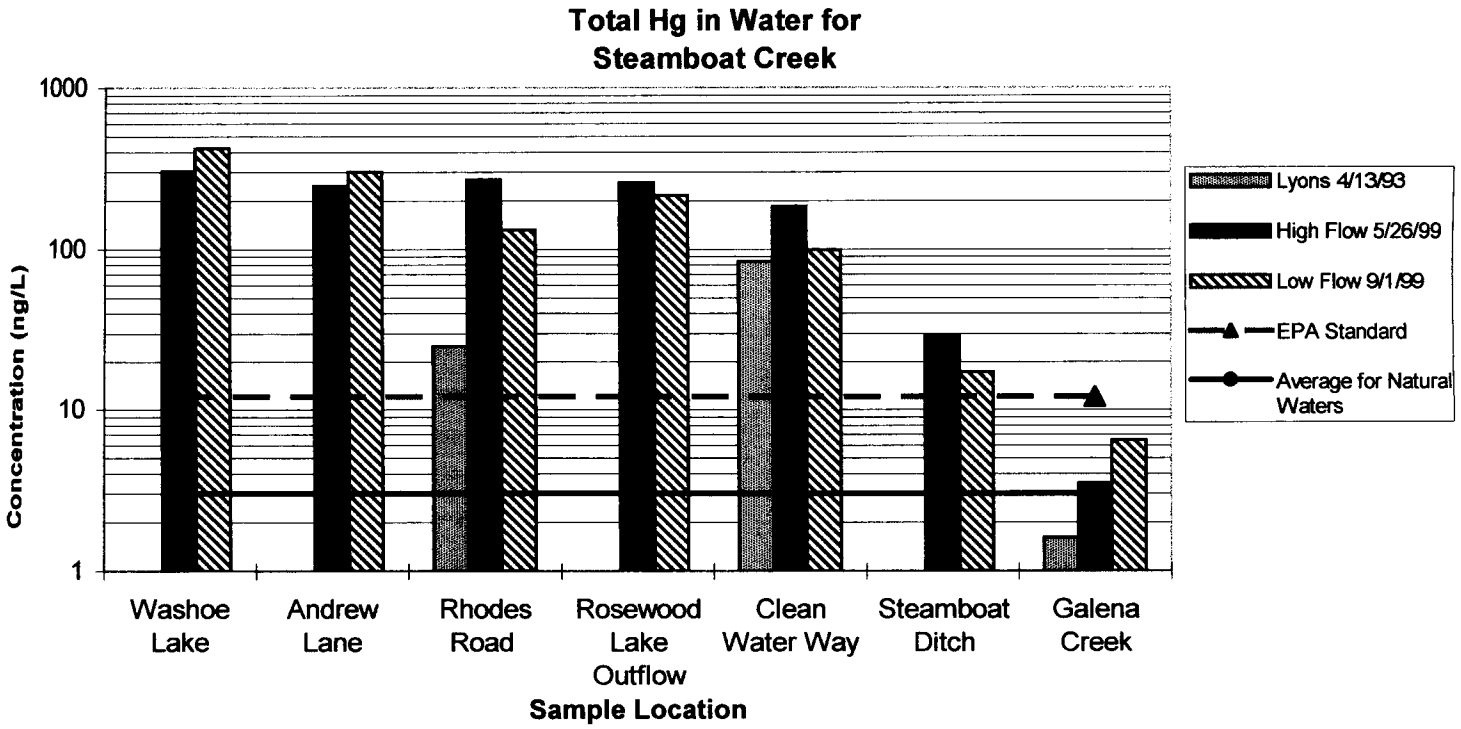

Figure 2. Total Unfiltered Mercury in Water (ng/L) Collected in May and September 1999. Table includes data of Lyons *et al.* (1998).

Methylmercury concentrations in unfiltered water samples at Washoe Lake Outfall and Clean Water Way were 1.4 ng/L and 0.63 ng/L, or 0.3 to 0.5 percent of the total, respectively. The single filtered sample taken at Clean Water Way had a methylmercury concentration of 0.46 ng/L.

Total mercury in Steamboat Creek sediments collected in May ranged from 0.26 µg/g to 3.40 µg/g for streambank deposits and from 0.30 µg/g to 7.13 µg/g for those in the stream channel (Table 2; Figure 3). Sediments collected in September had total mercury concentrations ranging from 0.59 µg/g to 6.15 µg/g for streambank deposits, and from 0.45 µg/g to 2.83 µg/g total mercury for those in the stream channel (Table 2; Figure 3). Total mercury in wetland sediments collected in September ranged from 0.62 µg/g to 10.5 µg/g total mercury (Table 2). Sediments collected from Galena Creek were below the Nevada Bureau of Mines and Geology's detection limit of 0.01 µg/g.

TABLE 2. Total Mercury in Sediments (µg/g) Collected From Steamboat Creek and Tributaries in May and September1999.

Sample Location	Streambank (µg/g)		Stream Channel (µg/g)		Wetlands (µg/g)	
	May 26	September 1	May 26	September 1	May 26	September 1
Washoe Lake Outflow	2.71	–	0.79	–	–	–
Washoe Lake Wetlands	–	–	–	–	–	0.62
Frog Pond	1.63	–	7.13	–	–	–
Frog Pond Wetlands 1	–	–	–	–	–	10.50
Frog Pond Wetlands 2						8.75
Pagni Lane	1.27	1.05	2.89	2.29	–	–
Andrew Lane	0.73	–	1.44	–	–	–
Rhodes Road	1.24	–	1.68	–	–	–
Rosewood Lakes Outflow	3.40	2.78	2.03	2.83	–	–
Rosewood Lakes Inflow	–	–	1.38	–	–	–
Clean Water Way	2.11	6.15	2.15	0.81	–	–
Airport Mitigation Site	0.26	0.59	0.30	0.45	–	–
Galena Creek	< 0.01	–	< 0.01	–	–	–

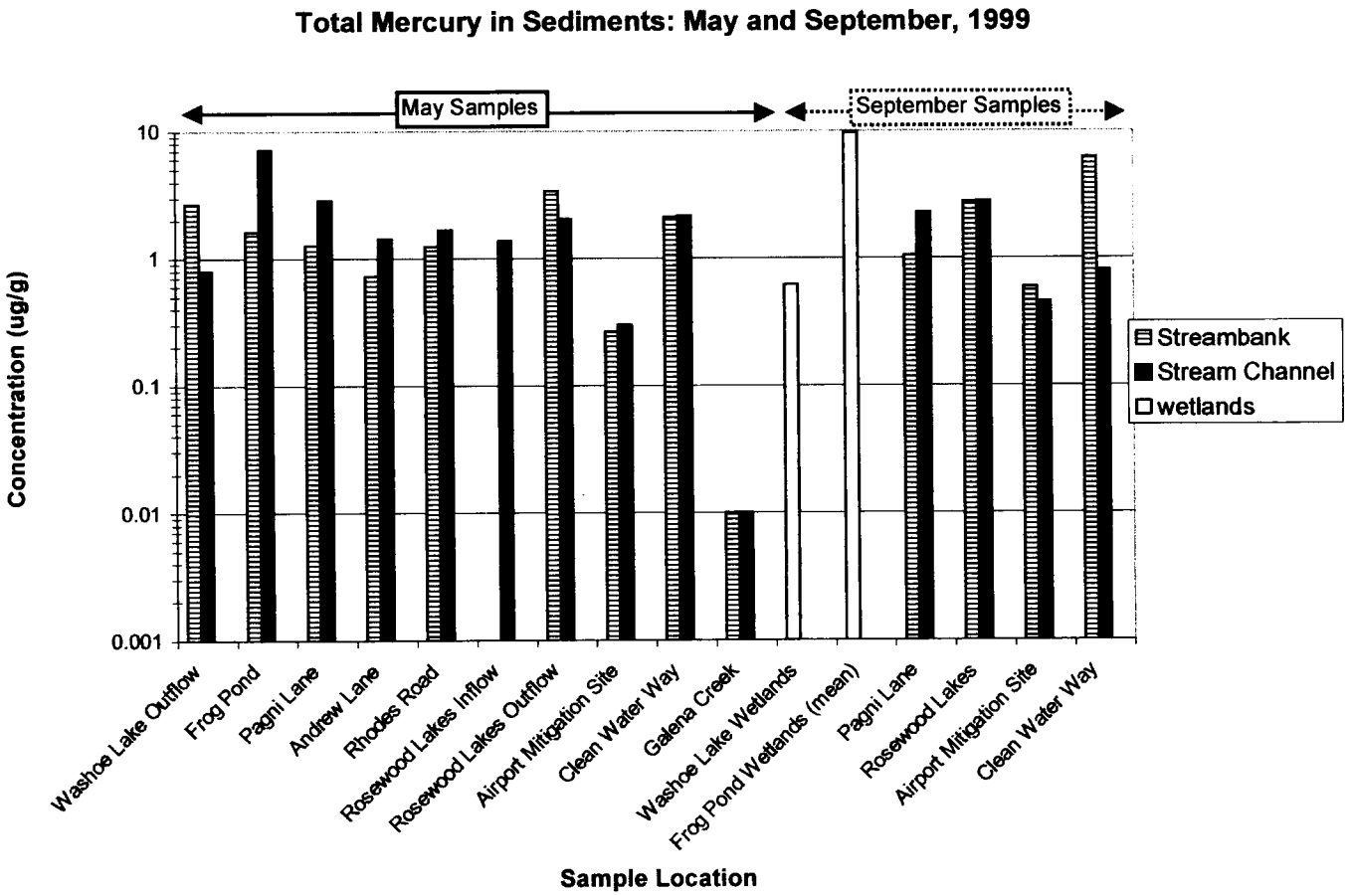

Figure 3. Total Mercury in Sediments (µ/g) Collected in May and September 1999. The sample denoted with (mean) indicates that the concentration is the average of several samples take at that site.

Methylmercury was measured in the sediment samples collected in September only. Values ranged from 0.12 to 1.7 ng/g for streambanks, 0.71 ng/g to 2.14 ng/g for stream channel (Figure 4), and 1.8 ng/g to 3.06 ng/g for wetland sediments. One-way ANOVA analysis ($P < 0.05$) revealed that methylmercury concentrations in wetlands were significantly higher than in stream channels and streambanks. Although methylmercury concentrations in stream channel and streambank samples were not significantly different, the following trend was identified. Mean methylmercury concentrations in wetlands (2.40 ± 0.52 ng/g) > stream channel concentrations (1.24 ± 0.62 ng/g) ≥ streambank concentrations (0.72 ± 0.69 ng/g).

DISCUSSION

Mercury concentrations in unfiltered waters of Steamboat Creek in 1999 ranged from approximately 80 to 420 ng/L (Figure 2). These concentrations are significantly greater than pristine waters (1-3 ng/L; Lindquist *et al.*, 1984; Gill and Bruland, 1990). Most (88 to 96 percent) of the mercury was not in the dissolved form or associated with particles of < 0.45 µm. Concentrations were considerably higher than the EPA Goldbook criterion of 12 ng/L (Marsheack, 1998) established to protect humans from fish consumption concerns due to the bioconcentration of mercury in food chains. The highest mercury concentrations in water were found at the headwaters of Steamboat Creek, the outfall of Washoe Lake, where mills were located that used mercury to process gold and silver ore in the late 1800s. Mercury concentrations in the waters of Steamboat Creek tributaries including: Galena Creek, Whites Creek, Thomas Creek, Alexander Ditch, Boynton Slough, and Yori Ditch, measured by Lyons *et al.* (1998) ranged from 1.1 to 2.7 ng/L. Mean mercury concentrations in waters of Galena Creek and Steamboat Ditch measured in this study were 5.0 and 23.5 ng/L, respectively (Figure 2). In order to assess the loading of mercury from the latter two sites to Steamboat Creek, flow data from 1998 for June and August and concentrations of mercury measured in this study, were used for the Galena Creek, Steamboat Ditch and the Rhodes Road sites. Flow data for Galena Creek and Steamboat Ditch were not

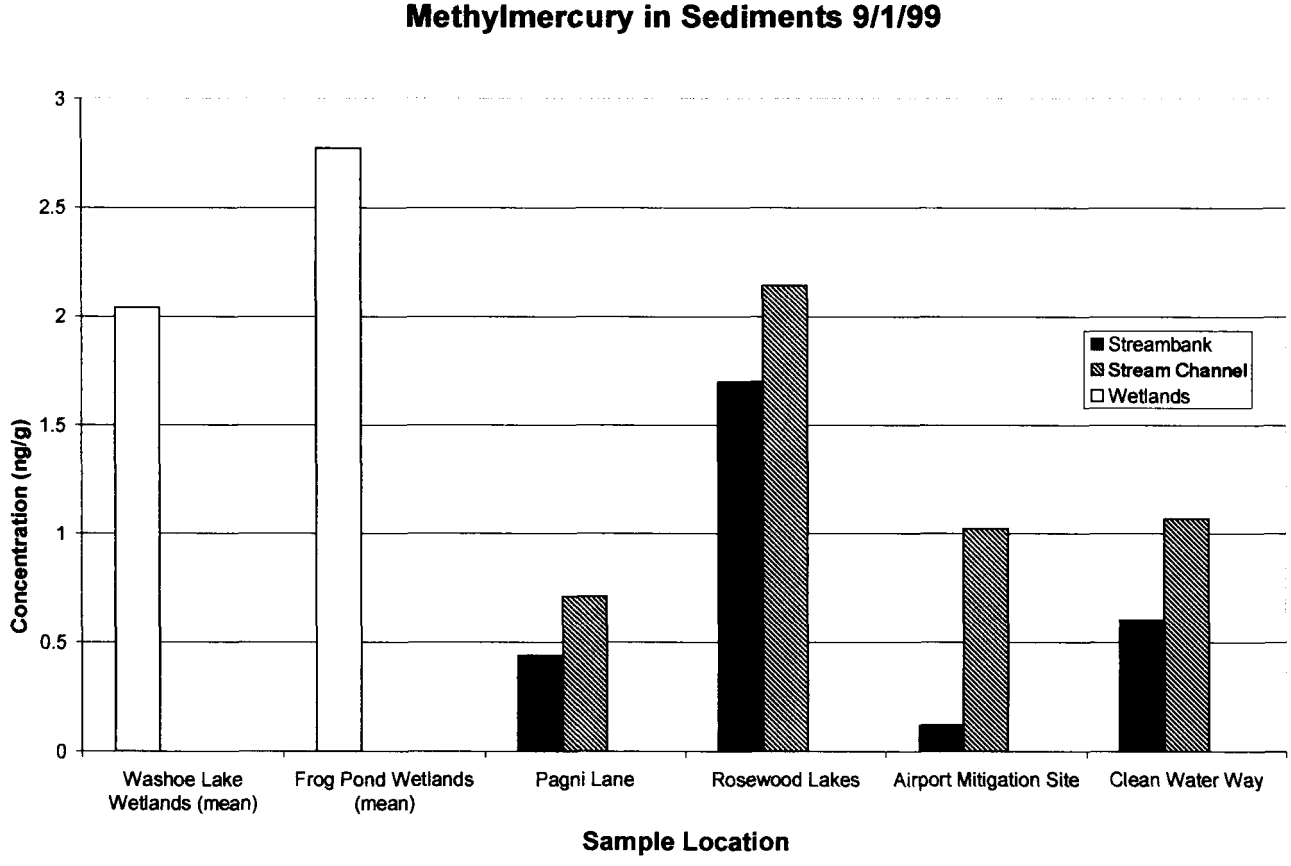

Figure 4. Methylmercury Concentration in Sediments (ng/g) Collected in September 1999. Samples denoted with (mean) indicate that the concentration is the average of several samples take at that site.

available for 1999 and, since gauged flows in 1998 and 1999 were similar in Steamboat Creek, we assumed that the 1998 flows were similar to those occurring in 1999. The calculated loads of mercury in Galena Creek and Steamboat Ditch that could have been contributed to Steamboat Creek in June and August were < 0.005 percent and < 0.1 percent of the mercury load calculated for Rhodes Road, respectively. Thus, tributaries to Steamboat Creek, including Steamboat Ditch which traverses a naturally mercury enriched geothermal area, contribute little mercury to the creek. This indicates that the primary source of mercury to the Creek is mill tailings that originated from the mills in Washoe Lake.

Flow data from the U.S. Geological Survey gauging stations at Rhodes Road and Clean Water Way for the two sampling dates were used to estimate daily loads of total mercury in water at these locations during the study (Figure 5). Loads were calculated by multiplying the flow for the day of sampling by the mercury concentration. Although total mercury concentrations in unfiltered water decreased downstream, loading increased. Loading also increased from Rhodes Road to Clean Water Way for the Lyons *et al.* (1998) data set. Because only minor inputs of mercury are derived from tributary streams and ditches, the source of increased loading of mercury in Steamboat Creek reflects resuspension of mill tailings that have been redistributed and deposited in the channel and on the banks of Steamboat Creek, for the past 120 years. A straightened, incised channel typifies much of the stretch between the two gauging stations, and there is significant development occurring along this reach. Degradation of the banks and channel bottom and subsequent resuspension of mercury-laden sediment due to development is thought to be the source of the increased mercury load in Steamboat Creek between the Rhodes Road and Clean Water Way gauging stations. In order to assess whether stream flows during sampling were representative of average conditions, the Hydraulic Engineering Center's Flood Frequency Analysis program was used to construct a Log Pearson Type III flood frequency curve from historic peak flow data for Rhodes Road (1962-1998) and Clean Water Way (1976-1998). The flows during sampling were 14 and 112 cfs at Rhodes Road, and 58 and 230 cfs at Clean Water Way. These were characteristic seasonal flows, corresponding to return interval ranges from 1.0 to 1.9 years.

Total mercury in streambank, stream channel, and wetland sediments were elevated well above the background concentrations measured in Galena Creek and what is considered natural background (20 to 650 ng/g; WHO, 1989). Substrate total mercury concentrations were higher in wetlands and where water velocities were relatively low due to lower gradients, shallower water, or wider areas of the channel (Table 2). In general, samples taken in May from the same location had similar concentrations to those taken in June.

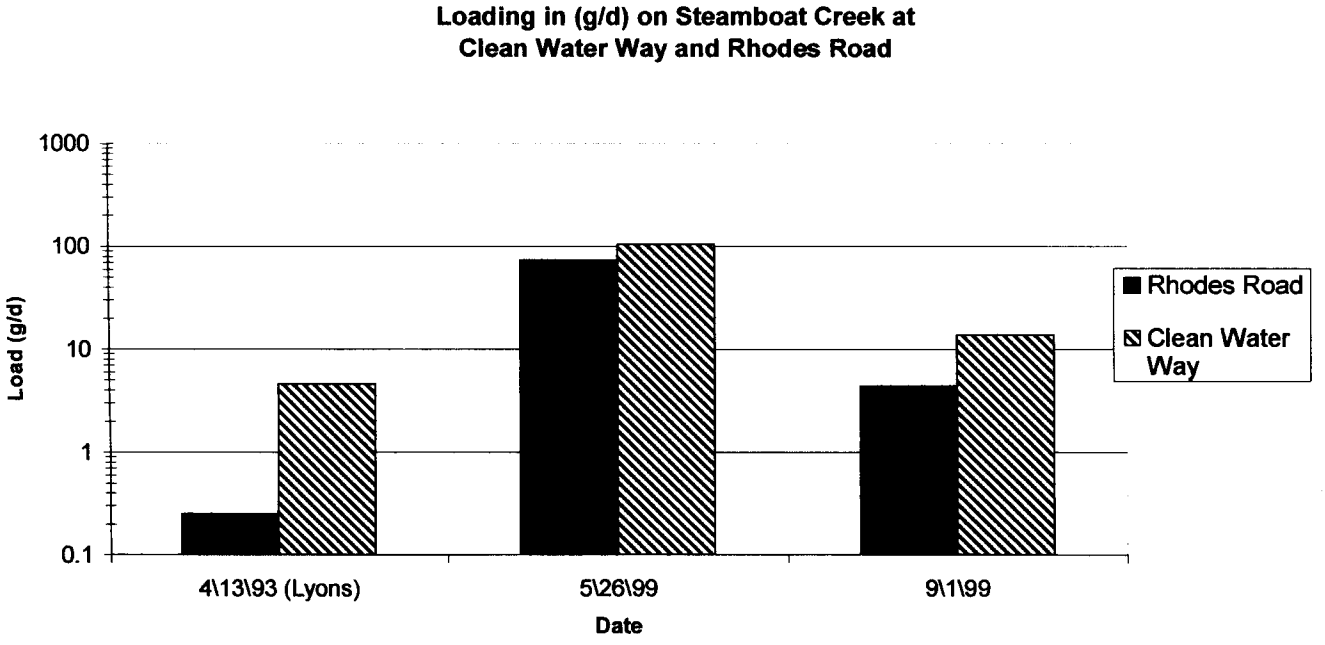

Figure 5. Mercury Loading for Rhodes Road and Clean Water Way (g/d) Based on Unfiltered Water Samples Collected in May and September 1999. Data from 1993 presented in Lyons *et al.* (1998).

Methylmercury in the water column represented a small percentage of the total mercury. However, concentrations are comparable to those reported for the mercury contaminated Carson River Superfund Site (cf., Bonzongo *et al.,* 1996) where human health warnings have been issued for fish consumption due to elevated fish tissue concentrations. The mean concentration of methylmercury in wetland sediments was approximately 70 percent higher than the mean of streambank sediment concentrations, and 50 percent higher than the mean concentration in the stream channel (Figure 4). Methylmercury concentrations increased as the environment became more anoxic from streambank to stream channel to wetland. This is consistent with studies suggesting that the majority of methylation in aquatic systems occurs in anaerobic environments, which are host to sulfur-reducing bacteria. Methylmercury concentrations in sediments are within the reported range for sediments in watersheds where health warnings have been issued for fish consumption, such as Clear Lake, California [0.64 to 14.2 ng/g dry weight (dw)] (Suchanek *et al.,* 1993), the Florida Everglades (<0.1 to 5.0 ng/g dw) (Gilmour *et al.,* 1998), and Lahonton Reservoir, NV (4.95 ± 0.97 ng/g dw) (Chen *et al.,* 1996).

CONCLUSIONS

From the information presented herein and in Lyons *et al.* (1998), it is evident that mercury contamination is present in both the water and sediments within Steamboat Creek. The origin of the mercury pollution can be attributed to the historic use of mercury in mining operations around Washoe Lake. Currently, continued release of mercury containing tailings from Washoe Lake and resuspension of tailings that were deposited in the channel and the banks of Steamboat Creek are contributing mercury to the Creek's waters. In recent years, this region of Nevada has witnessed significant anthropogenic disturbances due to development and increases in annual precipitation over the drought conditions that prevailed during the 1993 study. Elevated runoff and concurrent erosion resulted in higher total mercury concentrations in water relative to those measured in 1993 (Lyons *et al.,* 1998).

Wetland sediments contained higher concentrations of methylmercury than other riparian settings in this study. Methylmercury is produced in the top layer of sediments from inorganic mercury species (Gilmour *et al.,* 1998). Gilmour *et al.* (1998) suggested that methylmercury production could be correlated to methylmercury concentrations in sediments. Based on their observations, methylmercury production for Steamboat Creek is expected to be highest in wetland settings.

Methylmercury is the dominant mercury species in fish and the species of mercury that is bioaccumulated within food chains. Considering that methylmercury production in Steamboat Creek may impact fish in the Truckee River and Pyramid Lake, it is essential that restoration methods selected for Steamboat Creek do not enhance the production of methylmercury. While establishing wetlands could reduce mercury loading to the water column, wetland construction must be carried out with caution in this particular watershed, as it may lead to increased mercury methylation. Stream bank stabilization would reduce the remobilization of mercury stored in bank deposits, and could be beneficial in preventing further erosion of mercury-laden fluvial sediments. However, determination of the most responsible actions requires further assessment of mercury sources, transport, methylation rates, and fate with and without various alternatives. *In-situ* methylmercury production studies in different environmental settings are needed in order to assess the overall impact of stream restoration on the Steamboat and Truckee River systems. The sources, distribution, and movement of mercury within Steamboat Creek must be taken into account as plans for stream restoration and wetland mitigation are pursued.

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